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THERMAL BEHAVIOR OF GREEN ROOFS UNDER NORDIC WINTER CONDITIONS

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Abstract

To understand how green roofs affect building energy performance under cold climatic conditions, a proper thermal analysis of the roof and its components is required. To address this, we measured the thermal conductivity of each layer of experimental green roofs, as well as the equivalent thermal resistance of the complete green roof system during winter conditions in southern Finland. Green roofs were compared to bare roofs (without substrate, vegetation and other green roof layers) to assess the basic functioning and relative performance of the green roof system. Layer analysis at various intensities of frost penetration showed that the thermal conductivity of each layer decreased when penetrated by frost. In particular, thermal conductivity of the substrate and vegetation layers decreased from 0.41 $Wm^{-1}K^{-1}$ and 0.34 $Wm^{-1}K^{-1}$ prior to freezing, to 0.12 $Wm^{-1}K^{-1}$ and 0.10 $Wm^{-1}K^{-1}$ after freezing, respectively. This phenomenon is explained by a reduction in bridge-water connectivity during freezing and a volumetric water content that was below the critical threshold value. Overall, a frost depth that extended through the complete green roof yielded the greatest equivalent thermal resistance at a mean value of 2.01 m^2WK^{-1}. During times of snow cover, snow acted as an insulator and reduced the relative energy saving benefits achieved by green roofs. These results provide information for designing the substrate and vegetation layers of green roofs for optimal insulation.

Keywords: green roof, thermal conductivity, heat flux, energy saving, winter conditions

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1. Introduction

To make buildings more environmentally friendly, new energy efficient technologies and designs are continually sought after. A green, or vegetated roof, is a structural design approach that brings nature and engineering together to provide a sustainable alternative to conventional roofing [1]. Among the multifunctional benefits that a green roof provides, improved building envelope thermodynamics has been an important aspect for reducing energy consumption within the building sector [2,3]. As a living system, a green roof's thermal behavior is highly influenced by the surrounding climate. While it has been shown that they are effective tools for reducing cooling energy demands in warm and sunny climates [4–6], in cold climates, where heat energy demands dominate, there is still general uncertainty and a lack of research about how beneficial a green roof may be [3].

Winter thermal benefits achieved from a green roof system depend on vegetation type and material properties of the layers, including thickness, physical structure and thermal conductivity [7–9]. Commonly, the layers of a green roof from the top down consist of surface vegetation, substrate, filter/water retaining mat, drainage/root barrier, and a waterproofing membrane that all sit atop the structural support. When necessary, green roofs also utilize synthetic insulation at their base in order to ensure adequate thermal resistance [10].

A green roof will keep itself, and the building below, cool in the summer by means of evapotranspiration, photosynthesis and shading and yet remain an effective thermal mass in winter when vegetation is dormant and evapotranspiration negligible [11]. In comparison, an insulation system of only synthetic materials works well but is limited in performance due to constant thermal properties throughout the year. The synthetic system can thus only be optimized in terms of material thickness. Therefore, in designing for best annual energy use, indoor thermal comfort, and sustainability, application of a vegetated system in conjunction with minimal synthetic insulation, may provide the greatest thermal performance for Nordic climates [6,11–13].

A modelling study on four different climates in the United States has shown that green roofs have had greater heating energy savings in colder climates [14]. It has also been shown that roof and wall vegetation could considerably reduce heat loss through the building's façade in winter by reducing convective heat loss [15,16]. Thermal mass of the green roof has been shown to reduce heat flux through the green roof during winter, by 1-2 Wm^{-2}, and create more stable internal temperatures compared to a conventional roof [17,18]. Two studies conducted in the sub-tropical winters of Hong Kong have shown beneficial results for an extensive green roof (traditionally defined as green roofs with shallow substrates, see [19]) and negative results for an intensive green roof (with thicker substrates [19]). In the case of the extensive roof, roofing materials acted as a heat sink that released heat into the building during cooler nights [20]. In the case of the intensive roof, heat was lost from the substrate to the air, drawing warmer indoor air outwards [21]. In the French temperate climate, a green roof was shown to have very little impact on overall heating demands due to reduced heat losses during cold winter days along with a reduction in positive solar gains during sunny winter days [22]. Furthermore it was shown that snow effectively insulates buildings but scales down the relative benefits that a green roof can have compared to a conventional roof [2,23,24]. In the case of extreme weather conditions with sub-zero temperatures and severe wind and rain, the benefits of green roofs tend to increase [25], however, ice transfers heat energy more efficiently through its medium compared to liquid water [26], suggesting greater heat loss for frozen green roofs. Overall, given the variable performance in cold climates, a detailed understanding of energy loss and heat flux through green roof systems is still required.

Currently, very few studies have examined the thermal behavior of green roof layers during ice and snow conditions and none have exclusively evaluated overall or layer-specific thermal conductivity (k-values, see [26]). Since the thermal properties of a green roof vary significantly with moisture [7,27], and the thermal behavior of soil is affected by degree of frost penetration [28–30], it is important to develop k-values for the green roof and its component layers during winter conditions. Knowledge on the thermal behavior of the individual layers during times of freezing and thawing and different levels of frost intensity would enable a better understanding of green roof thermal performance and resulting heat flux under various winter conditions. A particular focus of this study is on the behavior of the substrate layer because of its complexity for design applications and because there are no current guidelines for the type of substrate to use for best thermal performance in freezing conditions.

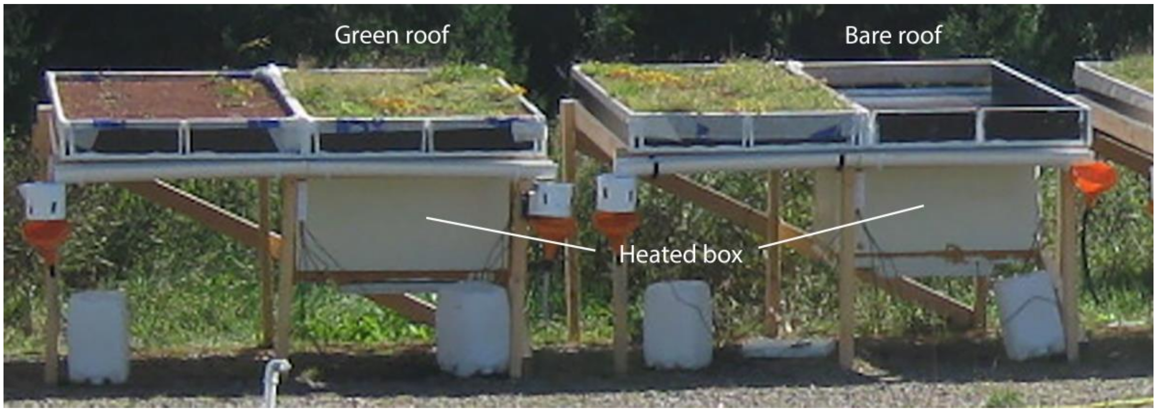
In this study we hypothesized that (i) frost penetration will increase green roof and green roof layer k-values, (ii) substrate is expected to exhibit a positive relationship between volumetric water content and k-values above 0 ^{o}C and a positive relationship between frost intensity and k-values below 0 ^{o}C, (iii) heat flux through the green roof will be less than the bare roof for the majority of the winter period, and (iv) snow cover will act as an additional insulation layer, reducing heat flux through both roofing systems.

2. Methods

2.1 Experimental setup

The experiment was carried out at Jokimaa, a University of Helsinki research station located in Lahti, southern Finland (60^{o}52'N, 25^{o}52'E), where winter is the dominant season, with long periods of sub-zero temperatures and snow cover that typically last 135-145 days [31].

Twenty-five roof platforms, each 1 m × 2 m in size at a height of 1.5 m were constructed at the station. Six of the platforms were used in this study (three green roofs and three bare or control roofs) (Fig. 1). The base, or supporting layer, was a 24 mm thick hardwood plywood. The bare roofs consisted only of the hardwood plywood support layer. For the green roofs, directly atop the plywood was an "Antico Rankka" moisture barrier sheet followed by a 25 mm thick water retaining and drainage layer made of molded polystyrene ("Nophadrain" [32]), hereafter referred to as the "drainage" layer. On top of the drainage layer was a 10 mm thick water holding filter fabric ("VT-filt": water storage capacity 8 l m^{-2}, [32]) used to prevent the loss of substrate particles and to retain water, hereafter referred to as the "fabric" layer. On top of these layers was a 50-60 mm thick substrate layer made of crushed recycled brick (85%), bark chippings (5%), peat (5%) and compost (5%; all percentages by fresh volume) (see Fig. 2 for particle size distribution).



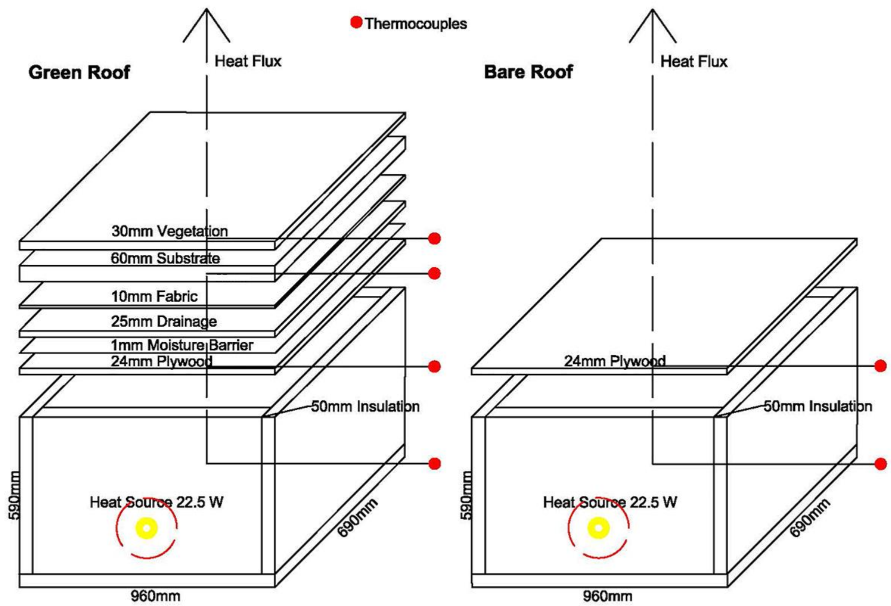


Fig. 1. Experimental green and bare roof setup (above) and schematic diagram of the systems (below).

The top layer was a pre-grown vegetation "Veg Tech" mat with a nominal thickness of 40 mm and supported drought resistant species of sedum, moss, and grass [32]. The dry density of the substrate and vegetation layers was on average 1.37 g cm^{-3} and 1.17 g cm^{-3}, respectively. A closed 0.30 m^3 (internal volume) insulated box was placed below each of the six roofing structures. The box had five walls made of extruded polystyrene, a housing insulation material ("Finnfoam 300/50") attached to the bottom surface of the plywood layer. All boxes were equipped with identical heating sources: a 25 W incandescent light bulb running at 90% inefficiency, 24 hours per day.

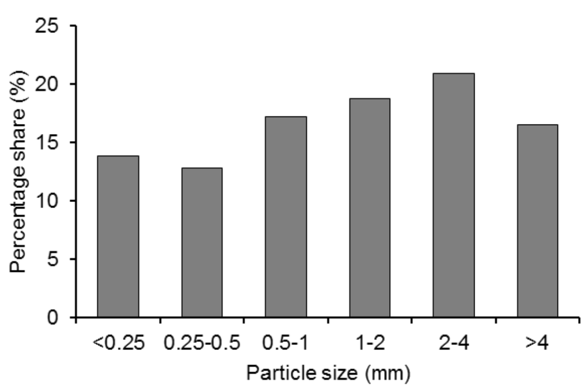


Fig. 2. The percentages of different sized particles in terms of dry weight for the crushed brick mixture, used as substrate in the green roof platforms.

2.2 Data collection

For the green roofs, thermocouples with moisture sensors were placed on the vegetation surfaces, within the substrates, on the top surface of the supporting structures (plywood), and inside the insulated boxes. For the bare roofs, they were placed on the supporting structures, and inside the insulated boxes (Fig. 1). Together the thermocouples were arranged in a vertical line that passed through the centroid of the insulated box. Temperature and moisture data were recorded at 20-min time intervals, 24 h per day at an accuracy of ± 1 ^{o}C and ± 3 % VWC [33]. VWC data were determined by measuring the dielectric constant of the media using capacitance/frequency domain technology at 70 MHz frequency and are reliable only in soil [33]. Data loggers ("Decagon devices Em50") collected the data. The on-site Vaisala WXT520 Micro Weather Station provided data on ambient air temperature and precipitation, and recorded data at 10-min intervals. Snowfall and snow depth information was obtained from the Finnish Meteorological Institute's Laune weather station, located 5 km from the experimental site. The measurement period for the roof ran from the beginning of October 2013 to the end of March 2014.

A linear one-dimensional temperature gradient was assumed in the vertical direction [34] and when the temperature of the thermocouple decreased below zero degrees, it was assumed that the layer and those above it, were penetrated by frost equal to the depth of the thermocouple. When temperatures decreased further, it was assumed that frost was penetrating further downward into the green roof. Since the fabric and drainage layer did not have thermocouples within them, temperatures from the thermocouple on the plywood surface were used to indicate that these bottom layers had frozen. All data were averaged over the three replications. Means and standard deviations reported assume normally distributed data.

Temperature data were separated into phases determined by level of frost depth penetration (Table 1). This was done in order to describe the effect of temperature on k-values during various frost intensity levels.

Table 1. Description of each phase used in monitoring green roof thermal behavior.

Phase	Level of Frost Penetration	Details
A	No frost penetration	Pre-winter, positive ambient temperatures, no snow.
B	No frost penetration	Thawing, positive ambient temperatures, snow on roof.
C	Frost penetration into vegetation layer only	Light sub-zero ambient temperatures.
D	Frost penetration into vegetation and substrate layers only.	Sub-zero ambient temperatures.
E	Frost penetration into all layers.	Intensive sub-zero ambient temperatures.

2.3 Theoretical approach

Heat transfer through the green roof is a transient process, however, because the aim of this study was to asses the thermal behavior of a green roof in cold climate, a steady state analysis was assumed to quantify heat flux. The steady state approach provides a quantitative estimate of k and R-values that are useful as a reference for qualitative interpretation of the thermal behaviour of the geen roof and its compnent layers [7].

A probilistic analysis on large samples of temperatures recorded provide most likely k and R-values and associated variance during each phase of frost penetration.

2.3.1 Conductive heat flux

The energy balance for roofing structures (Fig. 1) is given by:

$$Q_{\mathrm{roof}} = Q_{\mathrm{source}} - Q_{\mathrm{walls}}\ , \qquad (1)$$

where Q_{roof} is the overall heat flux through the bare or green roof surface, Q_{source} is the energy input from the incandescent light bulb, and Q_{walls} represents heat flux through the insulated walls of the heated box.

During winter, there is a temperature gradient through the roofing components of both the bare and green roofs due to the temperature difference between the warm inside air and the cold outside air. The majority of heat transferred from the interior outward in a green roof is through conduction [2,10]. Integrating Fourier's equation for steady state heat transfer, over the thickness of a medium, the mathematical model for heat flow by conduction is expressed as:

$$Q/A = T_1 - T_2/(L/k)\ , \qquad (2)$$

where A is surface area through which heat flux occurs (m^2); L is roof medium thickness (m); T_1 and T_2 are vertical temperature points (K), k is thermal conductivity ($Wm^{-1}K^{-1}$), and L/k is thermal resistance (R-values) for conduction (m^2KW^{-1}).

In locations where the temperature was not given by a thermocouple (interface of the vegetation and substrate layer, interface of the fabric and substrate layer, and the outside surface of the insulated box) an interpolated value was obtained by simultaneously solving for the k-values and heat flux of the corresponding layers.

2.4 Invariant thermal properties

Thermal conductivity and resistance of the insulating material (used for the heated boxes) and the plywood base are assumed constant throughout the experiment (Table 2). The thermal properties of these materials are a function of humidity and temperature, however at normal ambient temperatures any change is negligible in comparison to the other roofing components [35,36].

Table 2. Thermal resistance (R) and thermal conductivity (k) of materials used for both the green and bare roofs. Plywood R and k uncertainty = 10%.

	Thermal Resistance (m^2KW^{-1})	Thermal Conductivity (Wm^{-1} K^{-1})
Plywood (24 mm)	0.27	0.09
Box insulation (50 mm)	1.45	0.035

3. Results and Discussion

3.1 Green roof thermal conductivity

Green roofs resisted heat loss better than the bare roofs during all frost depth phases. Analysis of the various green roof layers show that k-values of the vegetation and substrate layers decreased as frost penetration depth increased (Fig. 3). Since the k-value of ice is about 4 times higher than water (k_{water} = 0.60 W m^{-1} K^{-1}, k_{ice} = 2.30 W m^{-1} K^{-1}) a corresponding increase in green roof layer k-values were expected during freezing, however, the opposite was observed. Correspondingly, green roof equivalent R-values increased as frost penetration depth increased, indicating that green roofs were better insulators during colder temperatures.

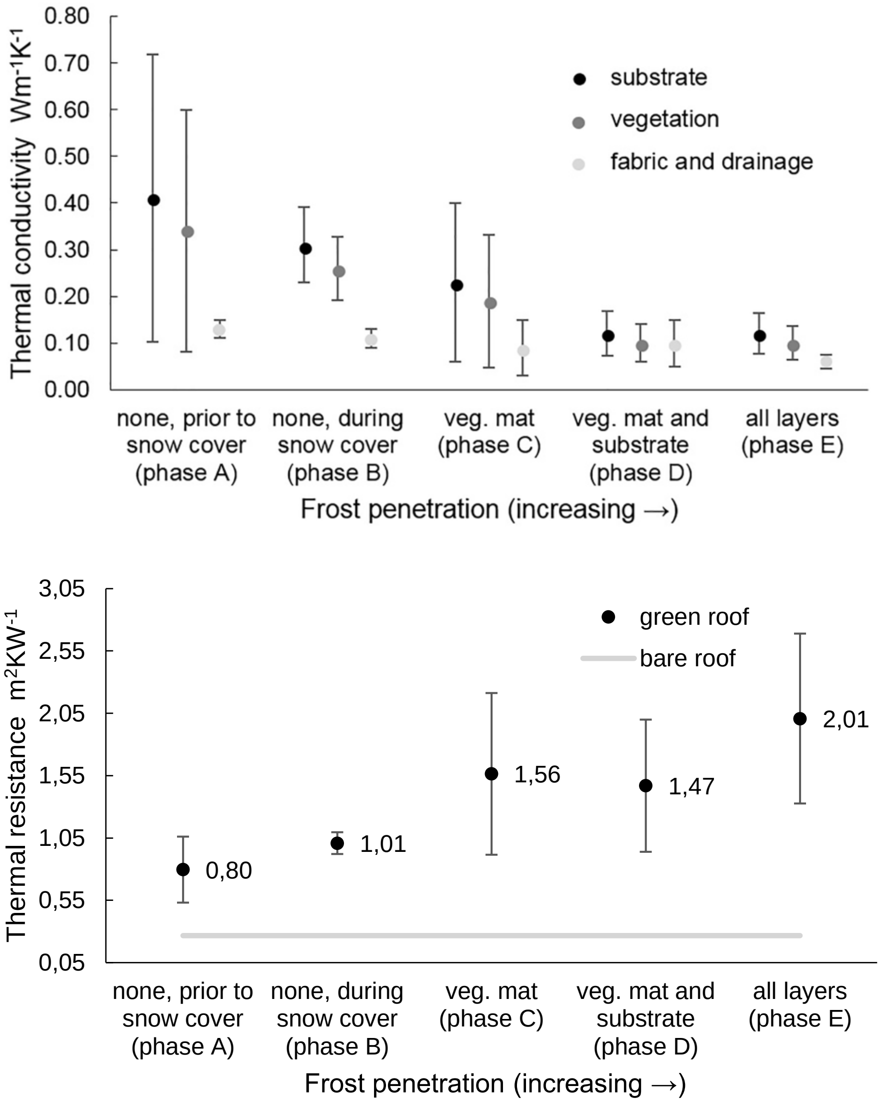


Fig. 3. Mean (± SD) thermal conductivity (k-value) of green roof layers (above) and equivalent thermal resistance (R-value) of green and bare roofs (below) during the different phases of frost penetration. Averaging time for each phase was 8-10 days.

During all phases of frost penetration, the substrate layer maintained the highest k-values with the vegetation mat having predominately the second highest values, slightly below those of the substrate. The fabric/drainage layer resisted heat flow the most, and its k-values remained relatively consistent throughout the winter season. Insulation properties of the fabric and drainage layers may be due to the large volume of stationary air held within the drainage structure [37].

Variation in k-values shows how vulnerable green roofs are to surrounding environmental conditions (see SDs in Fig. 3). However, variability was lower during snow cover on these roofs. In the case of no snow cover prior to frost penetration (phase A), variability of both the vegetation and the substrate was high, with a coefficient of variation (CV) of 0.76 and 0.75, respectively. High variation was also present during phase C, when there was frost penetration only into the vegetation layer (CV for the vegetation and substrate layers were 0.75 and 0.74, respectively). Variation is greatly reduced during the other phases, especially when all the green roof layers had frozen (phase E) with a CV of 0.36, 0.36, and 0.24 for the vegetation, substrate, and fabric and drainage layers, respectively.

A mean R-value of 2.01 $m^2 K W^{-1}$ achieved by the green roof, when all the layers were frozen, indicates that the system, while not as effective as synthetic insulation, has performed reasonably well as a thermal insulator during extreme winter conditions. Moreover, the reduction in k-values with decreasing sub-zero temperatures demonstrate a positive dynamic behavior that improves its thermal resistance, as higher values of resistance are desired.

It should be noted that green roof k and R-values are based on a simplified steady state analysis and the estimated values are more important for analysis of behavioral trends and relative performance rather than value accuracy.

3.2 The effect of volumetric water content on substrate thermal conductivity

The decrease in substrate and vegetation k-values during freezing may be explained by VWC and structural changes that occur within the layers when water turns into ice. In this study, only the substrate layer VWC was measured and an explanation on micro scale effects are discussed in relation to those measurements. VWC and corresponding k-values of the substrate layer throughout winter are shown in Fig. 4.

Prior to freezing (mid-October – late-November), VWC of the substrate had values fluctuating around 0.20 $m^3 m^{-3}$. This period had k-values corresponding to phase A. During times of thawing with snow cover (late-December and mid-February) substrate VWC was lower than it was prior to freezing despite the melting snow above the substrate. This period has k-values corresponding to phase B.

The first cold period began in November (24.11.2013) and ended in the beginning of December (05.12.2013). During this period, VWC decreased from 0.20 m^3 m^{-3} to 0.06 m^3 m^{-3} indicating liquid moisture reduction due to frost penetration. This period had k-values corresponding to phase C.

Phase E was experienced in January when temperatures decreased well below 0 ^{o}C, to minimum values of -20 ^{o}C. During this period, substrate VWC also reached its lowest point (0.02 m^3 m^{-3}), indicating that practically all the water in the substrate had frozen.

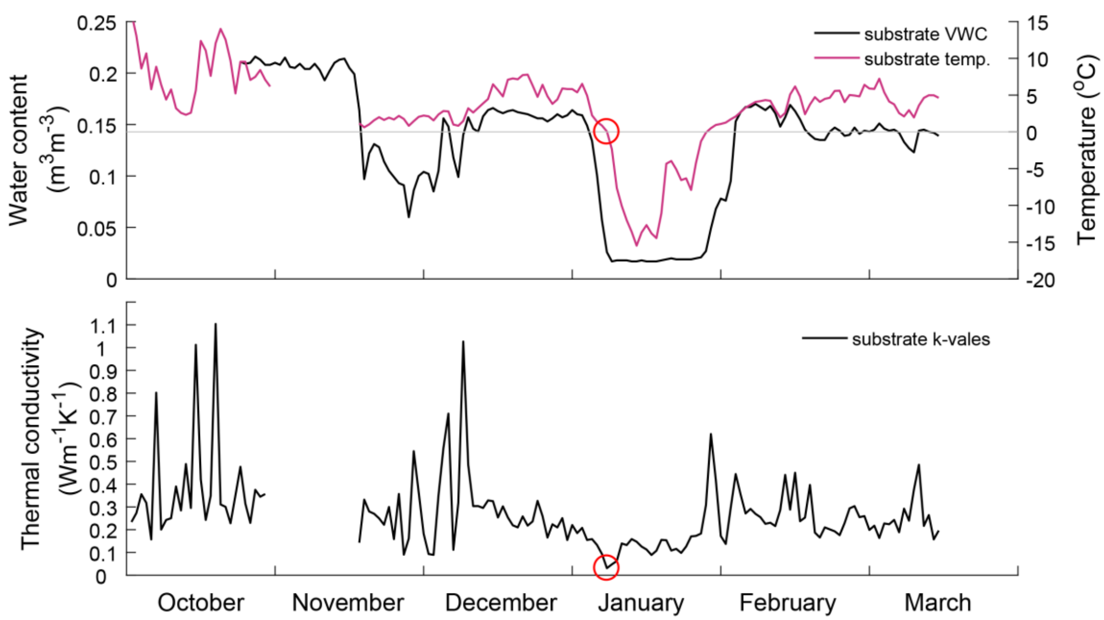


Fig. 4. Daily mean volumetric water content and temperature of the substrate layer at a depth of 5 cm (i.e. in the middle of the substrate) (above). Daily mean thermal conductivity of the substrate layer (below). The circles indicate initial frost penetration into the substrate layer. Missing information in the figures is due to one or more of the heat sources temporarily malfunctioning.

With increasing frost penetration, average substrate k-values decreased from 0.41 W m^{-1} K^{-1} in unfrozen conditions, to 0.23 W m^{-1} K^{-1} as frost started to penetrate the substrate layer. Finally, average k-value reduced to 0.12 W m^{-1} K^{-1} when frost had fully penetrated the layer. The reduction in k-values indicated that freezing of the substrate layer improved its insulative capacity, despite the higher k-value of ice. Furthermore, an immediate reduction in substrate k-values was observed during initial freezing of the layer (Fig. 5).

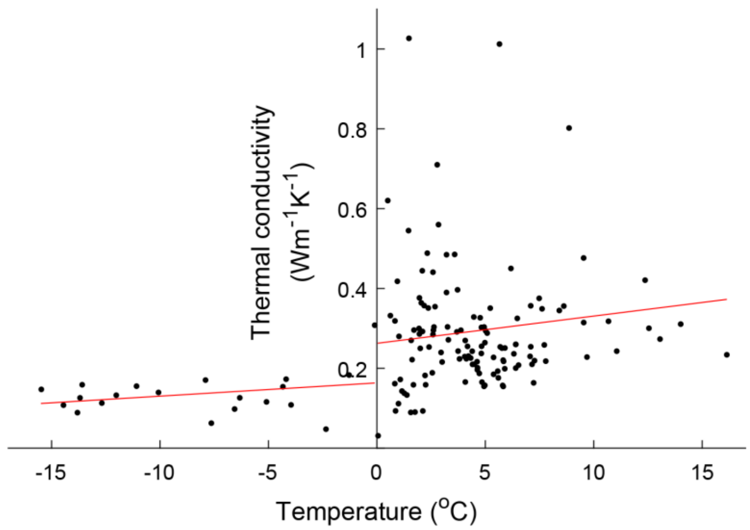


Fig. 5. Substrate daily average thermal conductivity scatter and trend lines, before and after freezing.

The different behavior of k-values before and after freezing may be explained by the bridge water effect at positive temperatures and particle discontinuity at negative temperatures. The basic features of these phenomena in freezing soils are explained in [28,38]. At temperatures above zero, the positive correlation between k-values and soil water content is due to the relative k-values of water and air (k_{water} = 0.60 Wm^{-1} K^{-1}, k_{air} = 0.024 Wm^{-1} K^{-1}). With increasing VWC, pore space within the soil is replaced with water and heat is then transferred through water, connected soil particles, as well as the additionally connected soil structure created by the water-to-soil bridging. Water that covers and lines the solid particles of the soil creates new points of connectivity between the particles, increasing the effective surface area available for heat transfer [28]. This is known as the bridge water effect and may explain the positive relationship between k-values and VWC observed at positive temperatures. Furthermore, since water in the green roof is dynamic [39], changes in particle connectivity would also be dynamic, explaining the large dispersion of k-values (CV = 0.75) observed during the unfrozen phases in Fig. 3. The positive correlation between substrate water content and k-values during warm conditions is in agreement with other green roof studies, e.g. [8,27].

At sub-zero temperatures, substrates can exhibit a reduction in k-values during freezing given the VWC is low enough. This phenomenon may occur due to a loss of connectivity within the layer as water molecules reform to create solid ice. The contact points and bridge water that existed in liquid form at positive temperatures are lost as solid ice crystals form. During this transformation, ice H-O-H molecules move inward and away from the substrate particles breaking connection points throughout the layer [40,41]. This disconnection within the substrate continues to develop as temperatures decline and more ice forms. The available surface area in which conductive heat transfer can occur is thus decreased and the substrate layer becomes a less efficient heat transfer medium [28]. Furthermore, the fusion process of water causes expansion and this may also result in substrate particle disconnection and increased void space as the heaving material moves outward. This phenomenon may explain the observed decrease in k-values for both the substrate and vegetation in our study (Fig. 3). The declining efficiency of heat transfer observed during decreasing temperatures was similar to various soils tested in [42] and [28]. Conversely, soils tested in [43] note a considerable increase in soil k-values during freezing and relate it to an extensive ice build-up (i.e. high VWC). A study that measured the k-values of frozen soils during phase transition reported an immediate increase in k-values at the point of freezing followed by an exponential decrease of k-values as temperatures continued to decrease [44]. Therefore, both increases and decreases in soil k-values are possible during freezing [28].

3.3 Critical moisture content

Theory suggests that there is a threshold VWC that causes soil k-values to increase or decrease during a phase change. It has been shown in various soils of various properties and aggregate size [30,40]. The relationship is not valid for every soil type but has been shown to hold true for several types, including coarse-sandy soils [40], thus corresponding to the rather coarse crushed brick substrate used in our study (Fig. 2). According to [28], when VWC is below a certain critical moisture content, the k-value of a freezing soil decreases when temperature is reduced and if it is above the critical VWC, an increase in k-values occur. In [30], the threshold moisture content was shown to be 15-20 % for the soil studied. The soil studied in [29] had a relatively high moisture content (45 %) and reported a 50% increase in winter k-values compared to summer ones. In our study, a decrease in substrate k-values was achieved during the freezing periods (Fig. 4), suggesting the VWC of the green roofs was below the critical moisture content. Prior to the November freezing period, VWC was 20 % and in January it was, 15 %.

The vegetation mat acted similar to the substrate layer and a reduction in k-values with decreasing temperatures was achieved as well (Fig. 3). With increasing frost penetration, average vegetation k-values decreased from 0.34 W m^{-1} K^{-1} in unfrozen conditions to 0.10 W m^{-1} K^{-1} when frost had fully penetrated the layer. The reasons for this may be the same as the substrate layer; however, VWC was not measured in the vegetation layer. Overall, the vegetation layer consistently acted as a better insulator than the substrate layer. This may be due to higher density of the substrate since a denser medium increases heat transfer efficiency, maintains unfrozen water longer and reduces permeability [28].

The importance of soil density on heat transfer was examined in [45] where it was observed that the k-values of a frozen soil, at negative temperatures, decreased with increasing temperature gradients and at positive temperatures, increased with increasing temperature gradients. However, since the density of the frozen soil was very low (0.81 g cm^{-3}) and the top soil had a lower temperature than the lower soil, convective heat transfer occurred causing the k-values of the frozen soil to be five times higher than k-values at positive temperatures. Therefore, determination of the critical moisture content for vegetation and substrate layers is crucial for green roof designs in Nordic climates, as long as conductive heat transfer is the dominating form of heat loss.

3.4 Heat flux during freezing conditions

During winter, the green roof performed consistently better than the bare roof in terms of heat flux. Due to additional thermal mass, the green roof had significantly less heat flux through the roofing system (paired *t*-test, $t = 1.731$, $p = 0.043$) most of the time, and less heat flux throughout the winter period (Fig. 6).

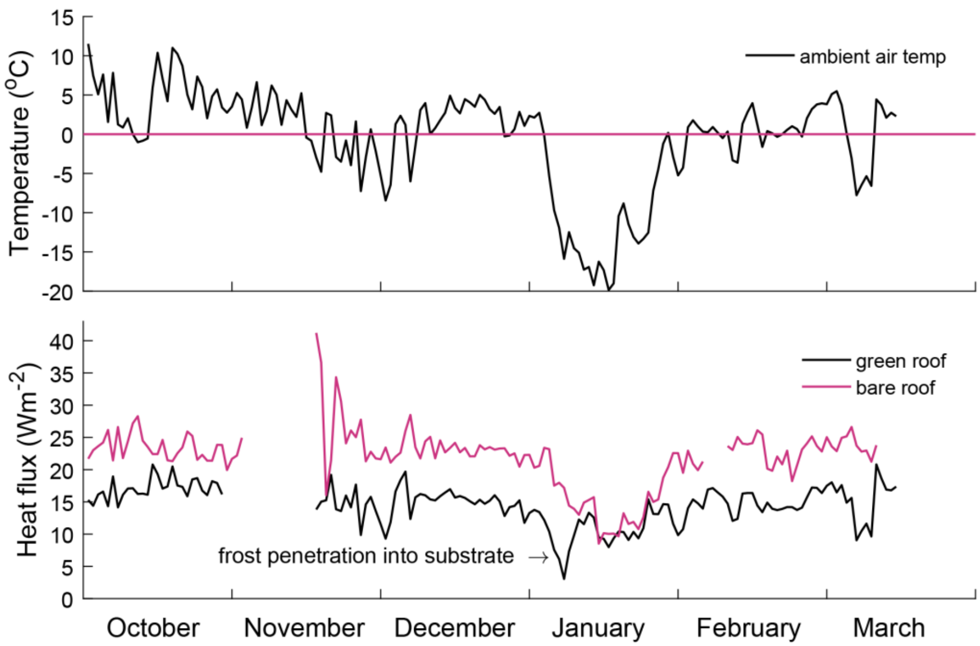


Fig. 6. Daily mean air temperature (above) and daily mean heat flux through bare and green roofs (below) during the winter of 2013-2014. Positive heat flux values indicate heat transfer from inside to outside through the roofs. The arrow indicates when frost penetration reached the mid-point of the substrate layer.

During the major freezing period in January 2014, there was an initial decrease in heat flux for the green roof (see arrow in Fig. 6). This happened when the vegetation and substrate layers were freezing and shows the strong effect of phase change on overall heat loss. However, the continuous decrease in temperatures was not accompanied by a continuous decrease in heat flux. This may be because snow had begun to accumulate on the green roofs, altering the overall heat flux of the roofs.

The largest difference in heat flux between the bare and green roofs occurred when ambient air temperatures were oscillating around 0 °C. This freeze-thaw period occurred at the end of November and the beginning of December 2013 when the green and bare roof heat flux had greater fluctuations compared to other winter periods (Fig. 6). Sudden and large reductions in green roof heat flux were observed during periods when ambient temperatures decreased below 0 °C and frost penetration into the vegetation layer led to immediate reductions in k-values.

Mean daily energy loss was equated from mean daily heat flux in order to compare the monthly reduction in heat loss achieved by the green roof. The addition of the green roof saved a significant amount of energy each month throughout winter, compared to the bare roof (paired *t*-test: $t = 5.593$, $p = 0.001$; Fig. 7).

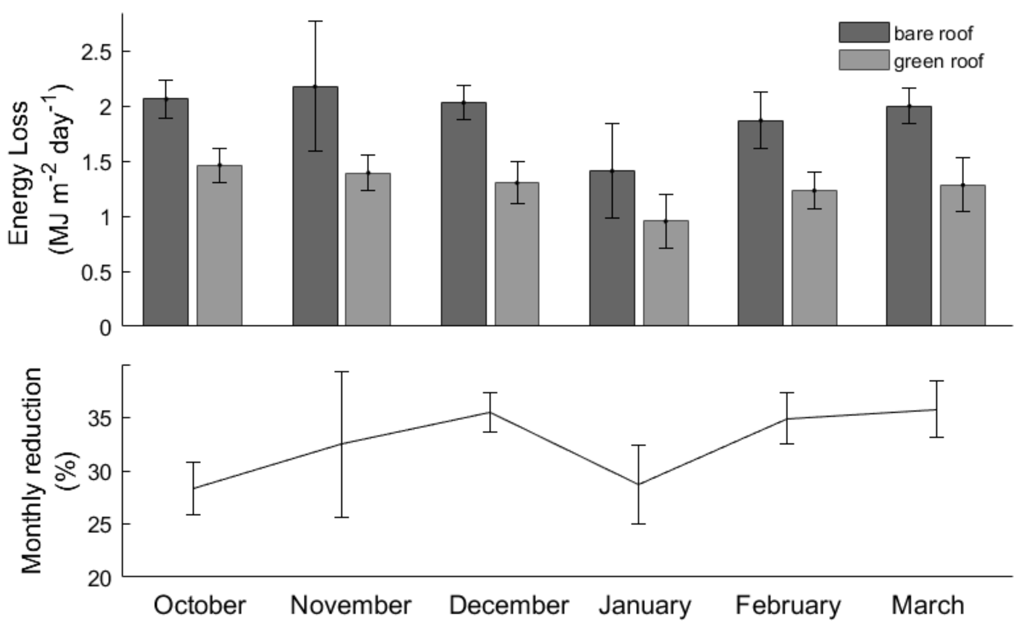


Fig. 7. Daily mean (± SD) energy loss through the bare and green roofs (above) and daily mean (± SE) percentage reduction in heat loss due to green roofs (below).

Overall, December 2013 and March 2014 were two months with the greatest reduction in heat loss. December achieved lower heat losses because of reduced temperature fluctuations and reduced k-values in the vegetation layer. The results during November and March may have occurred for the same reason as December. However, only partial monthly data were available for these months. October and January were months with the least reductions due to high VWC and the presence of snow, respectively. January was the month with the lowest amount of heat loss for both the bare and green roofs. The large reduction of heat loss in February may be attributed to the longer duration of snow cover on the green roofs compared to bare roofs during thawing.

Our experimental observations are a result of roofs without insulation and ambient air conditions on all sides of the heated box, including the bottom. Therefore, translations of our results to an actual building are not direct and emphasis is placed rather on the plausible causes discussed.

3.5 Snow cover

During consistent snow cover (approx. 20 days during the major freezing period in January and into February), both the green and bare roofs experienced lower heat fluxes. A more dramatic reduction in heat flux was exhibited by the bare roof compared to the green roof for the duration of the snow period, except at the beginning and end of that period (Fig. 6). At the beginning and end of the snow cover in January and during smaller snow events in December, snow cover remained on the green roofs while it melted on the warmer surface of the bare roof (Fig. 1). This lead to increased heat loss for the bare roof and increased energy savings for the green roof. The nullifying effect that snow had on the relative green roof benefits has been observed in other studies [2,3,12,46]. Despite the fact that snow reduces the relative benefits of green roofs when covering both rooftops, these vegetated roofs still benefited from greater snow depth, increased durations of snow cover, and reduced temperature fluctuations compared to the bare roof surface. Therefore, according to this study and [23], green roof designs that assist snow accumulation can also benefit from the natural insulative properties of snow.

4. Conclusion and future studies

To obtain information on the energy efficiency of green roofs in Nordic climates, the thermal behavior of the system and its components was assessed. A steady state analysis on heat flux through the roofs provided thermal conductivity values along with their relationship to frost penetration. Each of the green roof layer k-values decreased during freezing and a threshold VWC that determines whether vegetation and soil thermal conductivity increases or decreases upon freezing is proposed. Above the critical VWC, the layer's thermal conductivity value increases because of the large amount of highly conductive ice. Below the critical VWC, the layer loses connectivity during freezing and thermal conductivity is reduced. A substrate that drains optimally and holds moisture content below the critical volume (15-20%) can thus improve roof insulation during freezing. Correspondingly, green roof equivalent thermal resistance increased along with frost penetration and green roof heat flux remained lower than the bare roofs throughout winter, except during snow cover when a similar heat flux was observed. Future studies could validate our findings across various green roof soils with varying moisture contents.

Presented here are estimated heat flux and k-values determined from a one-dimensional steady state analysis on experimental roofs. Further studies should model the dynamic processes in which the effect of thermal mass, moisture and ice content, along with convective and radiative heat transfer are considered in a transient conduction model. In doing so k-values of greater reliability can be obtained and simulation programs (see e.g. [8]) may be updated for Nordic climate analysis. Other considerations should include the effects of material interfaces and three-dimensional heat transfer.

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